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Thermal injury to the feet poses a constant threat to military personnel deployed to cold and wet operational areas. Recently, a new type of insulating material that claims to store and release human body heat through a phase change process have appeared on the commercial footwear market. These phase change materials are typically based on parrafinic waxes and are encased in thin (1μ) microcapsules (15-40 μ in diameter). For footwear applications the microcapsules can be integrated into a thin, open cell foam, which replaces the traditional fibrous insulation, found in military cold weather boots. In this study, 8 volunteers wore the U.S. Army Intermediate Cold Weather Boot (Control), insulated with Thinsulate™ and three prototype boots identical to the Control but insulated with different phase change materials. The basic protocol consisted of walking on a treadmill at 1.34 m/s for 15 min followed by sitting for 70 min at 0° C and -12.3°C. Volunteers wearing the Control boot had consistently higher toe temperatures at 0°C but the lowest toe temperatures at -12.3°C. Volunteers wearing the prototype boot insulated with ComforTemp Foam™ phase change insulation had comparatively high toe temperatures at 0°C as well as the highest toe temperatures at -12.3°C.

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EFFECTS OF WEARING FOOTWEAR INSULATED WITH PHASE CHANGE MATERIALS DURING MODERATE COLD EXPOSURE

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INTRODUCTION

Thermal injury to the feet poses a constant threat to military personnel deployed to cold and wet operational areas. Significant cases of non-freezing cold injury occurring during military operations have been observed during long term exposure to both moderately cool/wet [1] and cold/wet [2,3] environments. Recently, new thermal insulating materials that claim to absorb and release body heat through a phase change process have appeared on the commercial outdoor clothing, handwear, and footwear markets [4]. A phase change material (PCM) can be defined as any material that has the ability to readily absorb and reject heat. Current manufacturing processes allow for specific transition temperatures at which point the latent heat of fusion of the PCM is either absorbed or rejected. For footwear insulation applications, PCM are microencapsulated and then integrated into foams or fibers that are incorporated into the lining of the boot. Encapsulation ensures that the phase change process can be continuously repeated without loss of any PCM. The PCM evaluated in this study were specifically engineered by the manufacturers to improve the thermal comfort of the human foot during exposure to cold ambient temperatures. The purpose of this present study was to compare thermoregulatory responses while wearing a standard U. S. Army boot designed for protection in cold–wet weather and a series of prototype boots insulated with PCM. These results along with other performance data will assist U.S. Army protective clothing developers with future decisions regarding the military use of these new insulating materials.

MATERIALS AND METHODS

Eight healthy males with an average age of 24 ±5 years volunteered for the study. The experimental procedures and potential risks were explained to all volunteers before obtaining their written consent. The protocol was approved by the U.S. Army Medical Research and Materiel Command Human Subjects Scientific Review Board. All volunteers wore a modified version of the U.S. Army Extended Cold Weather Clothing System (ECWCS) and a new pair of the test boots each day. The basic experiment consisted of walking on a level treadmill for 15 min at 1.34 $m \cdot s^{-1}$, followed by sitting still on a wooden bench for 70 min at 0°C and at -12.3°C. Temperatures of both small toes (T_{st}), both big toes (T_{bt}), rectal temperature (T_{re}), and a 3-point mean weighted skin temperature (T_{sk},°C) were continuously recorded. Prior to human testing, all four test boots were evaluated for both overall and toe region thermal resistance (R, $m^2 \cdot K \cdot W^{-1}$) using a heated foot model [5]. The four boots tested were the standard U.S. Army Intermediate Cold Wet Boot (Control), insulated with 3M Thinsulate™ and three boots identical to the control but insulated with different PCM: Frisby Technologies ComforTemp™ (Boot 1); Gateway Technologies Outlast No. 8088™ (Boot 2); and Outlast Cortina™ (Boot 3). The test temperatures (0 and –12.3°C) represent the upper and lower limits determining the issuance of the Control boot by the U.S. Army. Table 1 describes the test boots in detail regarding identification, physical location, and manufacturer of all protective materials.

Table 1. Identification and physical location of protective material layers for all test boots.

	Foot Skin Surface	→ → → → → → →		Boot Outer Leather
Control Boot	Cambrelle	200 g Thinsulate	Gore-Tex	200 g Thinsulate*
Boot No. 1	Cambrelle	ComforTemp Foam	Gore-Tex	200 g Thinsulate*
Boot No. 2	Cambrelle	Outlast No. 8088	Gore-Tex	200 g Thinsulate*
Boot No. 3	Eclipse 200S	Outlast Cortina	Gore-Tex	200 g Thinsulate*

ComforTemp™ phase change foam manufactured by Frisby Technologies, Clemmons, NC USA.
Outlast™ No. 8088 and Cortina™ microencapsulated phase change materials manufactured by Gateway Technologies, Boulder, CO USA.
Thinsulate™ microfilament polyester polyolifin manufactured by 3M Corp., St.Paul, MN USA.
Gore-Tex™ laminate material manufactured by W.L. Gore and Associates, Elkton, MD USA.
Cambrelle™ lining material manufactured by Faytex Corp., Weymouth, MA USA.
Eclipse™ lining material manufactured by Tempo Shain Corp., Salem, MA USA.
*This layer of Thinsulate was located in the upper shaft area only in all test boots.

RESULTS

Table 2 shows overall and localized thermal resistance values for all test boots using a heated anthropometric model of the human foot. Values given are for dry boot/sock combinations and after an 18 hour immersion in shallow water which effectively simulates a prolonged exposure to wet terrain conditions.

Table 2. Thermal resistance values (R, $m \cdot K \cdot W^{-1}$) for the overall boot, for toe sections only, and weights (kg) for all test boots.

	Overall-dry	Overall-wet	Toes-dry	Toes-wet	Weight-dry*	Weight-wet*
Control	0.242	0.208	0.233	0.161	1.01	1.12
Boot No. 1	0.237	0.205	0.240	0.167	1.11	1.26
Boot No. 2	0.231	0.205	0.225	0.161	0.99	1.10
Boot No. 3	0.239	0.215	0.233	0.167	1.01	1.11

All dry R values were means of 3 separate evaluations and wet R values from only 1 evaluation.
Wet R values calculated after Thermal Foot Model/test boot immersed upright in 7 cm of water for 18 h.
All boots were size 10 R and tested with the U.S. Army Standard Cushion Sole Sock.
*Weight of right-foot boot only.

Overall R of the dry boots was closely grouped. The highest value measured was with the Control (0.242) and lowest with Boot No. 2 (0.231). Overall wet R values were also closely grouped with both the Control and Boot No. 2 having the highest percentage reduction in overall dry R as a result of a 7 cm water immersion for 18 hr (14 %). Dry toe region R was highest with Boot 1 (0.240) and lowest with Boot 2 (0.225). Exposure to water caused toe region R values to decrease an average of 30% with the highest losses in the Control and Boot No. 1. Absorption of water during the 18 hr immersion caused boot weight to increase an average of 12% with the highest gain in Boot No. 1 (14%).

Figures 1 and 2 show the time courses of mean small toe temperature during both environmental exposures. Time courses of mean big toe temperature displayed similar temperature trends and rank order of test boot/final toe temperature at the end of the exposure. During exercise at 0°C, toe temperatures generally rose 3-4°C in all boots while gradually declining during the following 70

min period when the volunteers were sedentary. In general, toe temperatures rose slightly during exercise at −12.3°C while rapidly declining when volunteers were sedentary. Although mean final T_{st} and T_{bt} values were comparatively high with the Control boot in the 0°C environment, they were consistently the lowest in the -12.3°C environment. Mean final T_{st} and T_{bt} values were highest in both environments when wearing Boot 1.

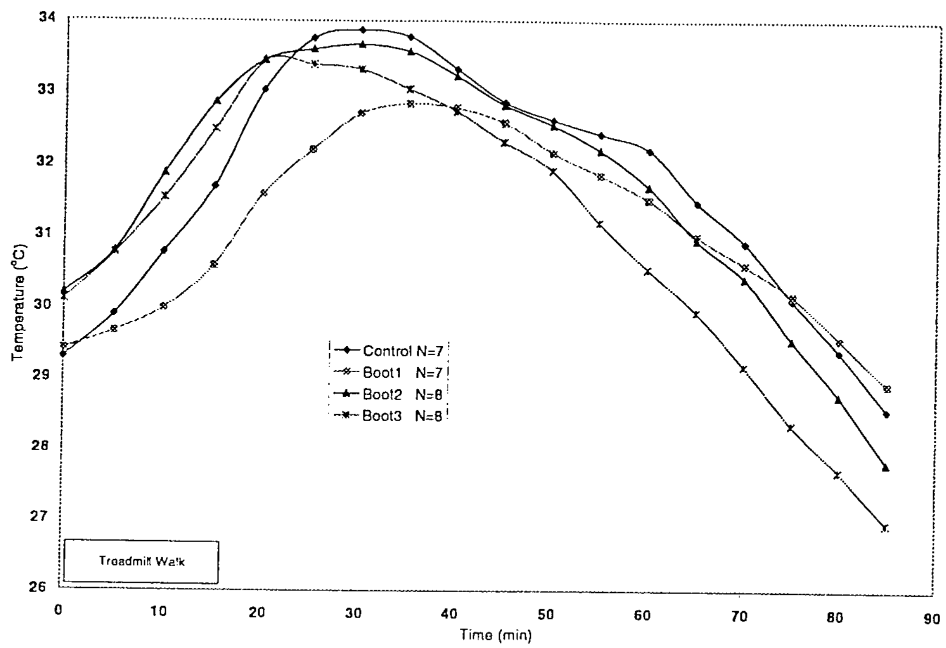

Figure 1. Mean small toe temperature at 0 C.

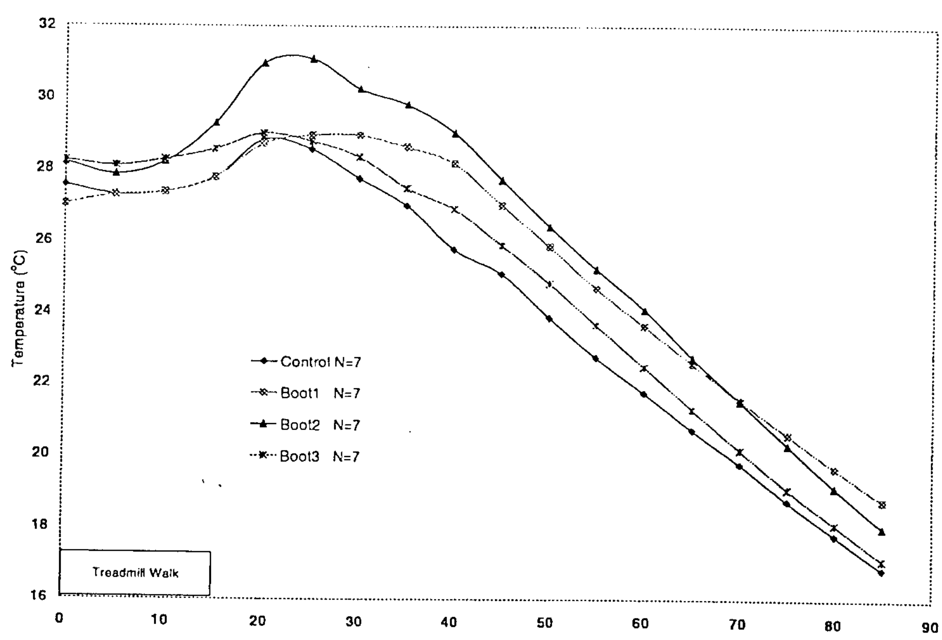

Figure 2. Mean small toe temperature at -12.3 °C.

Additionally, the general trend of the Boot 1 temperature curves showed that toe temperatures were cooler during exercise and warmer when volunteers were inactive. These trends also suggest that

endurance time would be longer with Boot 1 when compared to the other test boots if the cold exposures had been extended. There were no significant differences in T_{re} or T_{sk} between any of the four test boots during the two different environmental exposures.

CONCLUSIONS

Thermal foot model results showed that all test boots were closely grouped in terms of dry and wet thermal insulation with no particular boot indicating that it would provide an increased level of thermal comfort. The U.S. Army Intermediate Cold-Wet Boot, currently issued to personnel operating in cold and wet environments, provided comparatively high toe temperatures at the upper end of the issue temperature range but was less effective at the lower end of the range. Finally, these results suggest that the phase change material in Boot 1 contributed to maintaining both cooler temperatures during exercise and warmer temperatures while sedentary at the skin surface of both the small and large toes. This could provide increased comfort and protection when worn during a more extended cold exposure. It has been recommended that the U.S. Army continue to evaluate improved phase change insulating materials designed to increase individual thermal comfort and protection.

DISCLAIMER

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